Development of Morphology Analysis-Based Technology Roadmap Considering Layer Expansion Paths: Application of TRIZ and Text Mining

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Abstract: Morphology analysis (MA)-based roadmapping has been considered an effective means to support the process of technology innovation in a business environment. However, previous research on MA-based roadmaps has commonly focused on the process of developing existing technology roadmaps (TRMs), while the paths of layer expansion for seeking new opportunities is rarely a focus. Thus, the aim of this research is to develop MA-based TRMs by utilizing MA to describe the characteristics of the technology and product layers in the TRMs and apply the improved theory of inventive problem solving (TRIZ) inventive principles to establish innovation paths for new opportunities with the aid of text mining tools. This study suggests using a morphological matrix to construct existing TRMs by calculating the correlations among different technology and product nodes and two sparse generative topographic mapping (SGTM)-based maps to discover new technology and product opportunities by identifying technology and product development trends and innovation elements in sparse areas, which is the objective of simplifying TRIZ application. To illustrate the performance of the proposed approach, a case study is conducted using patents and product manuals for underwater vehicles, which are becoming popular high-tech and secure tools to explore sub-sea resources. This approach contributes by suggesting a semi-autonomous and systematic procedure to extend the existing MA-based TRM and simplifying TRIZ application according to the occurrence frequency of the keywords.

Keywords: morphology analysis; technology roadmap; TRIZ; text mining

1. Introduction

The industrial environment is currently experiencing its fourth revolution, which means as the individual needs of customers vary rapidly, product manufacturing and market strategic planning need to be adjusted in time according to changes in the situation [1]. To have a better position in the competitive market or have consumer preference, companies continually develop innovative technology and look for better products to launch for consumers [2]. Technology roadmap (TRM) is a useful technique to support and plan technology management and to link technology and product developments to business goals and market opportunities, which are tactics often employed by large companies [3]. According to a survey conducted in 1999 by UK manufacturers, approximately 10% of medium to large manufacturing firms in the UK have employed roadmapping [4], and this has now clearly increased.

A large amount of R&D capital and efforts were poured to encourage creation, such as through TRM, having been put forth by large firms to continuously generate new technology and products.

Nevertheless, these investigation activities normally require an amount of manpower and material resources that is too great for small and medium enterprises (SMEs) [5]. Another factor that becomes the obstacle for the use of the TRM approach is the shortage of appropriate input data on markets, competitors and technology, as such data often depends on knowledge connected by experts in forums and conference. Thus, suitable and effective knowledge management, as well as technology and product planning are becoming ever more essential to increase the economic profit, market share and technological status of a company.

To improve the capacity of SMEs to capture new opportunities in future markets, technology and products, the attributes of sustainability and low costs need to be considered preferentially in R&D management. As a widely used technique in R&D management, TRM is beneficial for organizations to plan their technologies by explaining the technologies, products, services and markets, which are the four layers obtained from previous studies. Each layer has its specific characteristics; for example, the market layer in the top is relative to trends of market, current needs of customers and potential customers, and it contains information on future development. In the middle, the service and product layers are related to the current service and functions and promising functions of products that customers need. At the bottom, the technology layer is related to the crucial information on trends of technology and issues of future [6,7].

Multiple previous studies on TRMs presented modified methodologies based on two perspectives: qualitative analysis, such as Delphi [8], morphology analysis (MA) [4,9,10] and the theory of inventive problem solving (TRIZ) [11]; and quantitative analysis, such as association rule mining [7] and Bayesian networks [12]. Yoon et al. [4] proposed the concept of MA-based TRMs to support planning and forecasting in SMEs with the criterion of data availability and tractability. Bloem et al. [9] proposed a methodology integrating MA with Delphi to refine the analysis results with the aim of providing good quality results for companies. Thus, the application of integrating MA in TRMs has been conducted widely in previous studies. Since TRM development needs professionals' support in fields of analysis and features of TRMs lie in the decomposition of the opportunities into four layers, the use of MA methodology becomes noticeable with other technology forecasting (TF) techniques [4,9]. The MA method aims to reconstruct the target subject broken down for exploring new structures [13]. The essence of MA is to analyze the target subject visually and derive novel ideas systematically, so it has the potential to be integrated with TRMs. Thus, combining the use of TRMs and other prospecting techniques, such as MA, TRIZ and text mining, can provide greater capability to analyze a sea of data, including patent documents, product manuals, customer feedback, service manuals, etc. [7], and to seek new opportunities systematically for firm development.

However, few papers focus on the process of seeking new opportunities in integrating MA and TRMs. In response, this paper proposed a methodology to utilize the results of MA as a basis of designing an existing TRM, while the forecast process was carried out with SGTM-based maps and TRIZ. The objectives of this paper are (a) to provide a comprehensive platform based on TRMs to integrate other techniques (TRIZ, mapping and computerized tools) in order to leverage the strengths of each part according to the modified form, (b) to explore a simplified pattern in TRIZ application according to keywords occurrence frequency and (c) to illustrate and discuss the application of the MA-based TRM methodology that proposed by the analysis of the development trends of underwater vehicles, aiming to seek new technologies and products in a visual way.

Differing from previous researches, this article intends to explore a systematic path of seeking new opportunities in virtue of the improved TRIZ inventive principles affecting the TRM platform established based on MA. In response to the huge system of TRIZ, this research is explorative and heuristic on the simplification of TRIZ application, while an applicable inventive principle is introduced creatively to meet the heterogeneous underwater vehicle field. Apart from this, the integration between MA and TRIZ inventive principles indicates a novel and standard thought which represents the interaction between innovation dimensions and innovation algorithms, increasing the universality of this method. Additionally, the structured hierarchical system of TRM fits the two qualitative innovation

methods well. To make the two qualitative methods more scientific and repeatable when analyzing complex systems, instead of relying only on the inspiration and experience of technicians, multiple text mining tools are applied to reduce the impact of experts' experiences.

In order to improve the capability of analyzing technology and product trends and seeking new opportunities, from the perspective of theory, this paper contributes by proposing a methodology that integrates TRMs with other management techniques. The paper also contributes to refining the applied techniques in order to leverage the strengths of each part by improving the process of constructing a morphology matrix with computerized tools as well as simplifying the application process of TRIZ compared to classical TRIZ to seek new opportunities for firms and governments. From the practical perspective, the application in the field of underwater vehicles combined with case studies is exploratory and heuristic in seeking potentially valuable technologies and products for new business opportunities in the target field. Furthermore, the system of this approach requires open-source data from online databases, decreasing the cost of research and development (R&D) costs for SMEs while improving the capability of identifying technological trends and perceiving market changes to ensure the competitiveness of the firm and its status in the industry.

The paper is structured as follows: Literature reviews on TRM, MA, TRIZ and text mining are demonstrated in Section 2. Section 3 is about the research framework. In this part, the research concept, the components of MA-based TRMs and the detailed procedure are described. Then, in Section 4, a proposed methodology for MA-based TRMs is illustrated with the underwater vehicle field. Section 5 is a discussion about the result of the illustrative study and several policies of the proposed methodology. Finally, in Section 6, the conclusions of this research are used to give possible directions for future studies.

2. Background

This section mainly reviews the background of TRM, MA, TRIZ and then, text mining based on previous literature.

2.1. Technology Roadmap

Initiation of an R&D project does not always possess the ability to come to fruition and to promote an innovative product or technology. As R&D organizations have limited resources, a project in an R&D organization has to repeatedly justify its reasons to exist alongside other projects [14]. Since TRMs first appeared at Motorola in the 1980s, they have been used as a tool in strategic integrated product and technology planning for R&D and they have been developed to a wider use in most industries [15]. The concept of a roadmap is combined with technology to assist project managers and technical analysts in aiming for a certain destination by choosing an ideal route among different alternatives and identifying the expected implementation time [5]. Figure 1 demonstrates the generic structure of a TRM as a time-based chart with several layers.

In the Collins Dictionary, the description of technology refers to methods, systems, and devices as the result of scientific knowledge that used for practical purposes. Stig et al. [16] proposed that some researchers used the term "technology" to refer to technologies that defined products and establish the rules for an entire industry, such as digital camera technology. The word "roadmap" shows a summary of scientific and technological plans in a way of maps, and the process of roadmapping is the evolvement of this roadmap [17,18]. Galvin [19] and Kostoff and Schaller [20] depicted a TRM as an agreement on the perspective of the future science and technology landscape available to people who make decisions. It provides a way to discover, assess and decide strategic alternatives to achieve a technological or scientific objective. Nathasit Gerdsri et al. [21] focused on the internal factors (e.g., technology development, R&D programs) and external factors (e.g., business drivers, market opportunities) in TRM to assess the status of a TRM. The use of technology roadmaps depicted in Figure 1 accelerated innovation in emerging technologies and product technologies, consolidating the

vision of the technical department to promote this strategic tool, which then was introduced by lots of organizations in different sectors in the world [8].
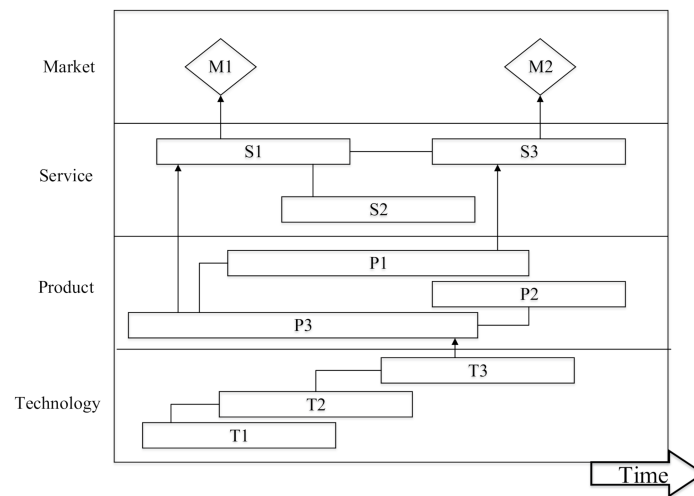

Figure 1. Structure of a technology roadmap.

The generic and time-based structure of a technology roadmap consists of layers, nodes and linkages between elements. These are the indispensable parts for fulfilling its basic aim [5]. The technology roadmapping approach has been combined with many qualitative methods like Delphi, brainstorming, scenario, the analytic hierarchy process (AHP) and MA for strategic planning because it produces plans of action for achieving goals [2]. The development of Delphi in TRMs is flexible in terms of the application process and the result of the application. Shim et al. [22] proposed a multi-analysis process by using patent analysis, Delphi and AHP analysis to make a TRM for the industry of eco-friendly building materials, and quality function deployment (QFD) was also tested to verify the study results. Castorena et al. [23] established an eight-step model integrated with a Delphi process with experts' help to find the common denominator for future technology directions. Brainstorming is always conducted to ensure the creativity and improve the quality of decision-making. Anna Azzi [24] organized a brainstorming session involving 10 representatives from 10 different companies to identify the most important influencing variables in inventory holding costs measurement, the result of which could be utilized as the basis of establishing a TRM for the company. Scenario planning has been employed as an effective tool with TRMs in many attempts in conducting one's decisions on alternative future environments. Ozcan Saritas and Jonathan Aylen [25] utilized scenarios to set the context for an exercise to inform the design of technology roadmaps and influence the wider policy context. Strauss and Radnor [26] invented a scenario-based TRM that integrates a TRM with scenario planning, demonstrating the encompassing key tasks, their interdependencies and the key decision points in the original TRM. Hussain et al. [27] integrated scenario planning and TRMs with a novel method. He first used scenario planning to find out reasonable pictures of the common environment and then used scenarios for technology roadmapping, followed by the advantageous use of 'flex points'—essential developments that signal transitions along certain pathways. Regarding the AHP, Li et al. [28] performed a technology assessment for critical techniques with a structuring AHP model. Lee et al. [29] developed a two-stage multicriteria decision making (MCDM) method that helped to make a long-term systematic energy TRM and utilized the fuzzy AHP to allot the corresponding weights of the criteria effectively. Tugrul Daim [30] utilized Technology Development Envelope (TDE), an extension of hierarchical decision modelling and AHP into the future, in order to yield multiple paths for technology development enabling organizations to build roadmaps depicting their strategies. For the development of MA in TRMs, Yoon et al. [4] proposed the concept of MA-based TRMs to support planning and forecasting in SMEs with the criteria of data availability and tractability. Bloem et al. [9] proposed a methodology integrating MA with

Delphi to refine the analysis results with the aim of providing good quality results for companies. Huang et al. [10] constructed a four-dimensional science and technology planning model including nation, technology, industry and risks and impacts for a nation seeking to combine future-oriented technology analyses (FTAs) with a national science, technology and innovation (ST&I) policy framework with bibliometrics and TRMs.

According to the previous literature, the development of TRMs reveal that their combination with other methods has been a crucial branch of study. This paper achieves cooperation between MA and TRMs by a novel method and applies simplified TRIZ in the process of seeking new opportunities to compensate for a chaotic innovation path.

2.2. Morphology Analysis

The core of MA is that the research object is resolved into several fundamental dimensions, which depict the object from a detailed and inclusive perspective. Each dimension can then be divided into several shapes to depict the characteristics of the entire system [13]. As Wissema [31] described, the basic procedure of MA has five steps: (a) the essential functions of the subject are defined, and its characteristics are divided into several dimensions. (b) All possible shapes of each dimension are listed to describe the dimension. (c) All combinations that can produce unique sets of shapes are investigated. The number of combinations can be calculated by multiplying the number of shapes associated with each dimension. (d) Evidence is sought for each combination through practical examples, and (e) the unfeasible combinations are eliminated, while the valuable combinations are retained and ranked by their significance.

To develop MA, valuable contributions have been made, and its application is the major research stream. MA has been employed in the design of technologies and computer-based designed products in TRM [9], technology forecast (TF) [32], technological opportunity discovery (TOD) [33] and the generation of business models [34]. Geum et al. [35] proposed a novel practical framework based on MA to integrate the models that are pulled by market and pushed by technology—considering both users and technological developments. The models pulled by market and pushed by technology have interconnections with the market and technology layers in TRMs, which could be used to explain the integration between MA and TRMs. Yoon et al. [36] suggested a methodology to explore opportunities of technology by connecting technology and products based on applying MA and text mining. The author classified the TOD results into three types, including existing, applied and heterogeneous products, based on the types of products and pointed out that the suggested semiautomated normative method could be useful for SMEs in strengthening the capabilities of TF, which is similar to TRMs. Im et al. [34] proposed a structured method to new business model development (NBMD) that enhances business owners promote, assess and choose the most advantageous business model to achieve business goals in two stages: one stage-based on MA while another based on a suitable business model.

Since the MA is a nonquantified modelling approach to identify, structure and analyze problems of technology, organization and society, it has been used to find possible substitutes in different fields in the world. MA has the potential to resolve problems by putting the conditions identified in each dimension together [34]. Consequently, MA is an appropriate tool to use in developing and generating the concept of the MA-based TRM model. Although MA is a superior method that has the potential to show future technology and product trends by brainstorming the ideas created by different professionals, its disadvantages lie in assessing and choosing the shapes in the morphology matrix that are best aligned with a field's development trends. To solve this problem of limitation, this study uses TRIZ and text mining tools as methods of evaluation and selection.

2.3. Theory of Inventive Problem Solving

Genrich Altshuller founded the TRIZ technique in Russia. It rests on the study of resourceful principles used in patents to obtain solution inspirations [37]. TRIZ provides a large set of inventive tools which can be used to identify, solve and understand problems [38]. Among the most common

characteristics of the TRIZ structure is its aim to determine compromises that could arise in the gap discovered by focusing on the root of a difficulty, resulting in clearly identifying the goal of the project [39]. There are four specific methods to a solution that can be chosen through the TRIZ methods according to the degree of involvement of the problem, which involve 39 engineering parameters and 40 inventive principles [11]. The fundamental process of using TRIZ is as follows: In the use of TRIZ in innovative design problem solving, the design engineer is responsible for first finding the contradictory things in the problem in existence. Next, the engineer puts each contradiction to two appropriate and corresponding parameters from among the 39 engineering parameters which are defined previously in the matrix. The engineer can then seek for inventive principles to solve the problem of engineering innovative design with the matrix when he or she verifies the parameters of the contradiction in the engineering system [37].

Thus, TRIZ contains a complete innovation system from the preliminary design phase to the conceptual design phase and design embodiment stage [40]. There have been many studies related to the application of the TRIZ innovation system [41,42], its combination with other methods [43–45] and improvements in the simplification of the TRIZ system [46–50]. In the previous studies, a strong point is the complexity property of TRIZ resulting from its large variety of techniques, which make the system difficult to understand and apply for ordinary engineers. Maimon et al. [51] developed the method of structured inventive thinking (SIT), inspired by TRIZ, to guide the search towards creative designs satisfying two sufficient conditions that characterize a subset of design innovations. Nakagawa et al. [52] noted that TRIZ typically led to confusing situations in its overall process due to having a large variety of techniques and therefore reorganized the TRIZ solution generation approaches into a less complicated set of five in unified structured inventive thinking (USIT), which simplified the system significantly. Tan [53] introduced C-TRIZ, which was a refinement of TRIZ, and constructed a mass-engineer-oriented training model (MEOTM) to support the dissemination of C-TRIZ and TRIZ. The author also noted that the market for C-TRIZ/TRIZ dissemination in the industry is becoming increasingly large in China.

Due to its capability of solving conflict problems, ideas for applying TRIZ in MA and TRMs are proposed in this paper. This paper first presents an effort to establish an integrated system consisting of TRMs, MA and TRIZ by providing a simplified application pattern for TRIZ. Toward this, an improved inventive principle called "intelligentization" is introduced to adapt the complexity of target field. The description is listed in Section 4.5. Additionally, computerized approaches play a crucial part in analyzing unstructured data and extracting valuable information in this study.

2.4. Text Mining

The important objective of text mining is to find out previously unknown knowledge from a large content of texts [54]. Most text mining tools have the assumption that keywords are used to label the essential part of documents, and therefore, operations for discovering knowledge can be performed on the document labels [55,56]. In conclusion, data mining employs machine learning and statistical analysis techniques in a database to automatically find patterns. Lots of efforts in data mining have made for the goal of obtaining information from a structured database, however, the usage of data mining is still restrained in handling large number of unstructured textual documents [57].

The general text mining methods for patent analysis could be classified as follows [58]: (a) document preprocessing. In this part, documents from online databases are collected and then segmentation and summarization of documents are conducted. (b) Indexing - keywords are extracted with the exclusion of function words and stop words prepared. MA, term association and clustering are conducted. (c) Topic clustering, which means the categories of the documents are clustered with the selected terms titling. (d) Topic mapping, which includes trend, query, aggregation and zooming mapping. In application, text mining is the process of analyzing an unstructured text information to obtain knowledge that users concern about and has potential practical value. With the experts intervened, text mining methodologies could become more intelligent for decision-making.

By using machine learning, text mining has been widely applied in patent analysis [59–64], knowledge management [65–67], TRMs [68], MA [69], etc. Based on the previous literature, machine learning techniques such as k-means and sparse generative topographic mapping (SGTM) are used to conduct clustering and forecasting in this study. K-means, which can divide data into k predetermined classes based on minimizing an error function, has been applied by many researchers in a wide range of domains because of its simplicity, efficiency and ease of convergence [70,71]. To achieve simultaneous data visualization and clustering, SGTM is developed by modifying the conventional GTM algorithm, which is always used in clustering motor unit action potentials and offers an approach of visualization as an effective tool for machine learning. Son et al. [72] suggested a patent map based on GTM and intended to naturally discover and illustrate technology vacuums, forming a grid-based two-dimensional map in which patents are mapped to the relevant grid. Kaneko et al. [73] developed an approach of sparse generative topographic mapping (SGTM) that cluster data points on two-dimensional maps, and the proper number of clusters is detained by optimization with criterion of the Bayesian information. Due to the usage of text mining tools, an MA-based TRM could be constructed in a semiautonomous form.

3. Methodology

This section will introduce the basic concepts and components of an MA-based TRM, the detailed research procedure and relevant applied quantitative tools.

3.1. Basic Concepts and Overall Process

This research proposed a new methodology for generating an MA-based TRM to look for new business opportunities according to a combination of technology and product morphology in a morphology matrix and an extension process incorporating TRIZ. Thus, we assumed that a company that possesses new technology that has not been promoted in markets or applied to products yet as well as transformed as structured documents explaining the technology and that it seeks new business opportunities through roadmapping. Taking an MA perspective, the process of TRM design starts by detecting a set of shapes from keywords that represent a technology with potential or concept of product. The suggested TRM is established based on existing technology and products by text mining and MA, by revealing the current situation of corporations. After roadmapping based on the current status, new chances for technologies and products are found through the inventive principles of TRIZ and experts' knowledge. The participation of TRIZ influences the process of technology foresight based on existing technologies and products.

This study was conducted to test the rationality of the framework of the proposed MA-based TRM, which focuses on two layers, the technology and the product. MA is usually applied to structure a problem by decomposing a system into some subsystems, identifying the morphology of the existing products and technologies, which contributes to roadmaps evolvement by the suggested new opportunities. Therefore, methods based on MA can be positive to the development of roadmaps by utilizing large volumes of product and technology data that might otherwise be inaccessible. The creative feature of TRIZ enables the process of technology foresight in TRMs to be less random and subjective. Furthermore, the framework of the proposed TRM allows quantitative and cyber-analytic tools to be combined to decrease the dependency on experts' knowledge.

The whole process in this paper consisted of five phases, as shown in Figure 2. First, proper data sources were identified to provide the MA-based technology roadmap for each layer. Patent documents and product manuals were collected from two different datasets for the TRM. The second phase was to find out the keyword list for each layer, denoting the technology and product shapes. Text mining tools were applied in keyword extraction and relative keyword vectors were generated consequently. Third, morphological matrix was constructed in this phase. K-means algorithm, the topic cluster algorithm and cosine correlation coefficient were applied to analyze the interconnections among the collected keywords. Following the identification of the relations among keywords, the overall morphology

matrix of the target research field was constructed for the definition of possible configurations of products and technology, providing opportunities for novel products and technology to be developed. Fourth, based on the morphology matrix, the existing TRM was accomplished by evolving the technological and product part of the roadmap based on the similarity between each pair of nodes, representing the multidimensional morphological relevance in this study. Finally, the SGTM-based map was established to identify sparse areas based on the extracted keywords, which contain the potential to future development. The MA-based TRM was extended through the SGTM-based maps during the technology foresight process and improved TRIZ inventive principles were used in concretizing the target field future development path. The additional possibilities of new technologies and products were analyzed by experts.
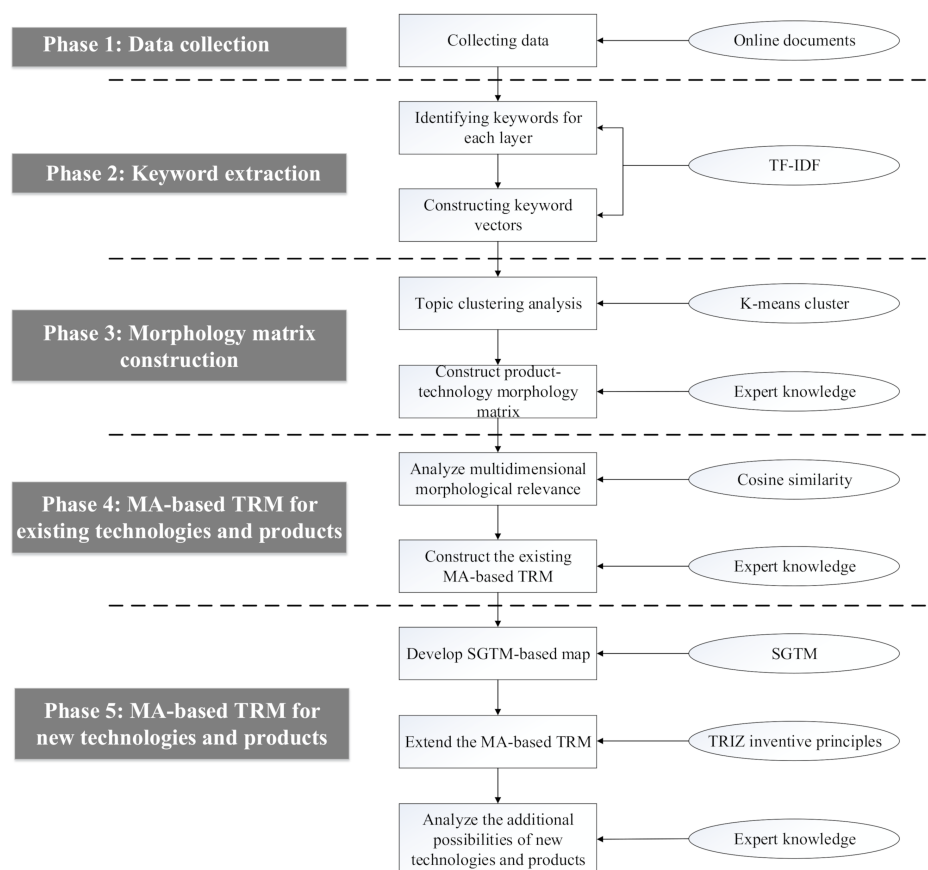

Figure 2. Research framework.

3.2. Components of an MA-Based TRM

The components of an MA-based TRM can be mostly put into three categories as layers, nodes and linkages. The definition of dimensions in MA was introduced to represent the layers in a TRM. The layers can be divided into technology, product, service and market layers, which are each listed above the previous layer. For example, the mechanism dimension is linked with the technology layer, the structure dimension is linked with the product layer, and the energy dimension is linked with the technology and product layers. There is a timeline covering all these layers to provide a criterion for identifying the interconnections among different layers. Generally, the left-hand side of a layer indicates point of the past, as the right-hand side of the layer indicates the latest point or a future time. In this study, the researchers chose the technology and product layers as the target layers to indicate the validity of the proposed approach.

The nodes located in each layer are the units of innovation concepts. The technology nodes in the technology layer indicate one technology or several technologies as a group, which consist of shapes in

MA. The technology shapes in the morphology matrix are the concepts subordinate to the dimensions in the category forming the technology nodes. Not very differently, every product node is located in the product layer, which indicates a product or a group of products that could be presented in the form of a configuration in MA. The configurations in MA that outline a product or technology indicate combinations of different shapes.

A linkage indicates a relationship between nodes. There are two kinds of linkages. The first linkage is between two nodes in the same layer, and the second is between two nodes in different layers. The direction of the developed technology can be found and technological similarity degrees can also be measured through the linkages between technology nodes. Moreover, through the connections of product nodes, the change and similarity of the products can be seen.

3.3. Detailed Procedure

In this section, the overall process introduced in 3.1 is described in detail, including five phases: (i) data collection and preprocessing; (ii) keyword extraction; (iii) morphology matrix construction; and (iv–v) MA-based TRM for existing and new technologies and products.

3.3.1. Phase 1: Data Collection and Pre-Processing

Importantly, MA-based TRM develops from data selection. The suggested methodology depends on quantitative analysis. To analyze documents to depict the important characteristics of each layer, text mining tools were utilized to deal with the large amount of data information and extract keywords. Appropriate data sources should be selected for each layer, including the technology and product layers in this study. Patents were considered as technology documents because patents are critical elements for technology analysis, and they also help promote several kinds of science and technological development. In this study, patent documents included essential items: titles of inventions, abstracts, specific descriptions and claims, and were gathered from the database of the US Patent and Trade Organization (USPTO). Regarding the product layer, product manuals extracted from professional websites are used to analyze product information, such as mechanisms, functions and energy sources. The technological content of patents can be linked with designing products. A product manual usually deals with content concerning the product itself, which could be effectively utilized to enrich the information of the technological shapes in MA in turn. Both the patent documents and product manuals are preprocessed by a Python program to remove stop and function words and split the sentences into single words, with the aim of simplifying the process and improving the analysis results.

3.3.2. Phase 2: Keyword Extraction

As the information in patents and product manuals is too extensive to allow effective analysis of the technological development trend, a set of keywords that represent the main characteristics of documents was used to address the chaos of information overload, and then an MA-based TRM was developed by considering keywords as the basic elements of nodes. Many studies have extracted keywords through text mining techniques from patent or product manuals and then utilized them to develop a morphology matrix [74], a patent map [56], or a TRM [75]. Text mining techniques were utilized to extract keywords from the above mentioned content with the aim of transforming unstructured data into valuable structural data automatically, which was suitable for constructing document vectors and morphology matrices in the subsequent phase.

In this study, keywords are filtered through several steps. First, all the collected documents were preprocessed in Python. Word segmentation was carried out to break the patent documents into different words and prepare for the second step. For instance, the sentence "The product consists of five parts" was divided into "The", "product", "consists", "of", "five" and "parts". Second, the function and stop words in all the collected documents were taken out to avoid unnecessary effects. For instance, "The" and "of" were moved out to cut down the burden of specialists. Third, the keywords of each layer were extracted independently and automatically by the term frequency-inverse document frequency

(TF-IDF) method, which determines the importance of a word to a document in a collection from the preprocessed documents, as shown in Table 1. Thus, a TF-IDF matrix of different types of data was established for identifying a list of keywords for each layer. Fourth, domain experts who are capable of identifying the relevance of the keywords were engaged in filtering out unnecessary and irrelevant technology or product keywords. The keyword list of each layer was generated in this step. Fifth, after deriving the keyword lists, the document vectors were constructed based on the TF-IDF values. A document vector contains the TF-IDF value of each keyword, representing how important each keyword in a layer is in a document in a quantitative way, as shown in Table 1. The TF-IDF value of keyword k in patent document n and product manual m is demonstrated in the rows of Table 1. For instance, the value of keyword 1 is 0.022, and the value of keyword 2 is 0 in patent document 1. The similarity between documents could be observed by making use of these document vectors. The similarity, which shows how closely each document is relative to other documents, was used to associate the nodes in the MA-based TRM.

Table 1. Example of a term frequency-inverse document frequency (TF-IDF) matrix based on patents and product manuals.

TF-IDF Matrix: (k, m + n)	Patent 1	Patent n	Product 1	Product m
Keyword 1	0.022	0.15	0.059	0.214
Keyword 2	0	0.247	0.48	0.59
Keyword k	0.169	0.01	0.159	0

3.3.3. Phase 3: Morphology Matrix Construction

Traditional MA relies on intuition of experts since MA has no systematic method that identifies the dimensions and shapes that are used to fill in the content of the nodes in an MA-based TRM. To overcome these limitations, this study adopted keyword-based MA to analyze the inner mechanisms of technology, the overall structures of products and the relationship between the technology and product layers in a semi-autonomous way. Based on the keyword lists derived in Phase 2, the technology morphology, the product morphology and the hybrid morphology of the technology and products were developed to describe the main characteristics of the target research field hierarchically. The configurations of different shapes were used to fill in the content of the nodes in the MA-based TRM.

This process was implemented through two steps. In the first step, a data-driven k-means clustering approach was used to analyze the interrelationships of the innovation elements. In this step, the technology keywords and product keywords were classified into different groups automatically according to the k value in a specific interval, which represents the distance between the keywords and the central point. However, the clustering results obtained with the k-means algorithm are insufficient for combining the keywords with the technology or product features. For this purpose, in the second step, a process of qualitative analysis—a similarity-seeking and topic analysis process—was carried out to construct the morphology matrix. During the process of this step, expert judgement played a crucial role in defining the topic of each cluster. Experts selected proper keywords and clustered the keywords by using their professional knowledge. The overly nonspecific and unimportant keywords were excluded in each cluster. The morphology matrix was constructed after the two steps.

A traditional k-means algorithm must set the k value manually, and this value has great impacts on the clustering results. In order to weaken this influence and to find the best k value in a certain interval, our approach employed the research of Bholowalia [76], an optimized algorithm based on k-means and the low-energy adaptive clustering hierarchy (LEACH) protocol through simulation experiments, which can determine the best k value in an interval to ensure the overall distance between different clusters is as great as possible while the distance between the vectors in each cluster is as small as possible.

3.3.4. Phase 4: MA-Based TRM for Existing Technologies and Products

Based on the morphology matrix, technology and product roadmaps were developed to depict the development trend in the form of technology and product configurations, which were identified by the values of dimensions and shapes represented by extracted keywords. As a consequence, new potentially essential configurations could be prioritized from the alternative lists, and a technology or product roadmap made along a timeline could be created as a plan for new technology or product development.

The process was carried out in two stages. The first concerns the multidimensional correlation analysis of different dimensions and shapes. To identify the combination paths scientifically, the similarities among the dimensions and shapes should be considered as the judgement criteria. The cosine value of two vectors can be derived with the help of the Euclidean dot product Equation (1)

$$\text{Similarity} = \cos \theta = \frac{A \cdot B}{\|A\|\|B\|} = \frac{\sum_{i=1}^{n} (A_i \times B_i)}{\sqrt{\sum_{i=1}^{n} (A_i)^2} \times \sqrt{\sum_{i=1}^{n} (B_i)^2}} \tag{1}$$

here *A* and *B* indicate document vectors. The similarities values between each pair of technology nodes, product nodes and technology and product nodes were calculated to assist experts in identifying configurations of previous technologies and products by connecting certain keywords with the morphology matrix. Based on the cosine coefficient, the similarity between keywords, documents, and keywords and documents were identified. For the other step, which relates to the construction of the MA-based TRM, the linkages between pairs of nodes were built based on the similarity values calculated in the prior step, and the position of each node is corresponding to the time concept of the layer.

3.3.5. Phase 5: MA-Based TRM for New Technologies and Products

Considering that MA-based TRMs for existing technologies and products may point the way to constructing organizational environments or breaking down complex problems into less complicated problems, the methods of facilitating creative thinking for new technologies and products may not be creative and systematic enough; this largely depends on the experts' knowledge. To overcome this limitation, an SGTM-based map, which is utilized to identify a technology sparse area as an innovation source, is established, while the innovation path from the source to new technologies and products is determined by TRIZ, which provides a tool for the performance of delicate and complicated mental operations by using an extensive analysis to. The codes for the SGTM method are obtained from Kaneko et al. [73].

Thus, this process was conducted in three parts. First, the SGTM technique was used for mapping, as it was useful in identifying sparse areas objectively. Based on the keyword vector generated in the prior step, two two-dimensional maps were developed to provide more concrete and detailed guidelines. Then, following the SGTM-based maps, 40 TRIZ inventive principles were systematically applied to the path of technology and product innovation. There are six steps to simplify the application of TRIZ in this part. First, the keywords of each TRIZ inventive principle were generalized from the definition collected from the TRIZ journal based on expert participation as the representative innovation elements. Second, the collected patents were processed by removing unnecessary words like stop words (such as "the", "on" and "in"). Then, stemming was performed to transform the patents and keywords of the TRIZ inventive principles into basic forms of stems to improve the efficiency of analysis. For example, "sep" means "separate," and "meas" means "measurement". Third, text mining techniques were used to extract the core inventive principles by calculating the frequency of the appearance of these keywords in the collected patent documents. Fourth, based on the result of the prior steps, the 40 TRIZ inventive principles could be ranked to facilitate the process of identifying new technologies and products in the MA-based TRM. Fifth, the technology sparse areas were refined by the ranked TRIZ inventive principles. However, the concrete time when the technologies and products

will be invented was not included in this research, and it can be developed in future research. New technology and product opportunities were identified after that.

4. Illustration: Technology Roadmapping in the Case of Underwater Vehicles

In this section, we will introduce the illustrating examples of underwater vehicles to illustrate the applicability of the proposed approach and the results related to the future underwater vehicle technologies and products development.

4.1. Phase 1: Data Collection and Pre-Processing

To explain the process of the proposed approach, this study chooses the field of underwater vehicles. Most consumers may ignore underwater vehicles because of the difficulty of understanding the specifics of the relevant technology embodied in the products, such as the systems and components. New product development is pushed not by consumers' needs but rather by advances in technology [2]. The suggested approach is based on technology because it includes the concepts and prototypes of products, and the hierarchical structure of complex underwater vehicle technology is identified to provide firms in the underwater vehicle field with a feasible and promising strategy.

The sea is the second largest space for human development after the land among the four major strategic spaces: land, sea, air and sky. It is also the strategic base for the development of biology, energy, water and metal resources and the most realistic space with the greatest potential for future development [77]. In this study, 155 patents whose application dates are between 2000 and 2019 were retrieved from the USPTO database, and 150 product manuals were targeted for analysis from the website www.nauticexpo.cn. To make the analysis more accurate and effective, the collected documents were preprocessed in Python, a machine learning language. Word segmentation was implemented to divide the patent documents into single words and stop and function words were removed to prepare for the next phase.

4.2. Phase 2: Keyword Extraction

In this phase, the keywords of two layers—a technology layer and a product layer—are extracted to identify the features of technology and products and to construct the morphology matrix. Many studies of knowledge discovery in texts are based on the assumption that a group of keywords in a document represents the topics of the given document.

The keyword list for each layer was developed via a two-step process. First, the TF-IDF matrix: (155, 5171) based on the patent documents and the TF-IDF matrix: (150, 2706) based on the product manuals were established automatically by Python. This means that there are 5171 keywords extracted from 155 patent documents and 2706 keywords extracted from 150 product manuals. The results of whole TF-IDF matrixes can be found in the Supplementary Material (TF-IDF of patents and products). According to the quantitative process, the preliminary features of underwater vehicle technologies and products can be determined based on the keywords. Second, several domain experts conducted a qualitative filtering process. When choosing technology keywords, keywords that are relative to technological features (e.g., localization) and possible components of the technology should be selected. Similarly, when choosing product keywords, keywords that are relative to the structure (e.g., battery), material (e.g., titanium), etc. should be prioritized. A total of three experts with more than 10 years of experience in designing and constructing underwater vehicles were invited to supervise the selection process of keywords. As a result, 206 technology keywords and 106 product keywords were extracted as the research targets in constructing the morphology matrix.

4.3. Phase 3: Morphology Matrix Construction

To construct the morphology matrix, ambiguous relations among keywords from different documents are addressed by an optimized k-means cluster algorithm that can select a k value of 30 automatically. In the morphology matrix, there are four dimensions: the mechanism (representing

the technology layer), structure (representing the product layer), material and energy (both representing the technology layer and product layer) dimensions. The subordinate concept of dimension is that of shapes, which are grouped by the keywords extracted from the collected documents. Based on the clustering result of the technology layer, the relation to the keywords in each group is analyzed by experts, and the topic of the clusters as well as the shapes are defined as depicted in Table 2. The complete clustering results of technology keywords are listed in Appendix A. For example, in Table 2, the topic of cluster 1 is defined as omnirange, as there are keywords relevant to omnirange (e.g., acoustic, gps, usbl and ins).

Table 2. An example of K-means clustering results of technology keywords.

Cluster_ID	0	1	10	11	13	17
Keywords	flash automatic transmission processor solid window float fuel bulkhead polyurethane roller clamp directional impeller hover	Acoustic gps usbl iridium ins	Lithium housing umbilical pulse aluminum ballast copper	Optical lbl antenna backscatter wifi	Internal fiber lcd composite jet converter	Battery lbs motor pitch propeller
Topic	Mechanical arm Motion form Buoyancy material	Omnirange	Equipment carrying system	Underwater localization	Buoyancy material, hull	Energy source, propeller

Based on the clustering result of the product layer, the relation to the keywords in each group is analyzed by experts, and the topic of the clusters as well as the shapes are defined as depicted in Table 3. The complete clustering results of product keywords are listed in Appendix B. For example, in Table 3, considering the actual result, the *k* value is adjusted to 15 to make the result more significant and valuable. The topic of cluster 1 is defined as sensor after analyzing the interrelationships among the keywords of sensor, gps, strobe, telemetry, laser, altimeter, transponder, antenna, didson and echosounder.

Table 3. An example of K-means clustering result of product keywords.

Cluster_ID	1	4	6	8	10	11
Keywords	sensor gps strobe telemetry laser altimeter transponder transmission antenna metal didson echosounder hipap polyurethane	skid crawler plastic beam winch minirov chassis wood polypropylene container nuclear ahrs polymer foam acrylic transmitter pvc conductor glass	ethernet transducer generator hydrophone body hydraulic buoy magnetometer receiver bandwidth micro usb wifi rdf bulkhead filter adds tracker	manipulator console joystick motor arm lcd waterproof gyro halogen nylon grp lamp	cable battery lithium connector	steel energy fiber aluminium polyethylene copper titanium
Topic	Sensor	Winch, buoyancy material, hull	Emergency localization, hull	Mechanical arm	Battery	Hull, transmission media

Based on the results of analyzing the inner relevance between chaotic innovation elements in Tables 2 and 3, the whole morphology matrix is constructed to depict the performances of underwater vehicle field as shown in Table 4. The mechanism dimension consists of keywords from patent documents, while the structure dimension consists of keywords that are mainly from product manuals and partly from patent documents to make the morphology more abundant. For the material dimension and energy dimension, the shapes are extracted from the two clustering results.

Table 4. Morphological matrix for the underwater vehicle field.

Dimension	Shape	Keywords
Mechanism dimension (Technology layer)	Communication system	Cable, waveguide, coils, radio, acoustic, satellite
	Equipment carrying system	Winch, bracket, umbilical cable, cable, coils, transmission, ballast, appendages, manual, cage
	Camera	Camera, sensor, beam, interface, high sensitivity, converter, solid, low light, field
	Underwater localization	Sonar, detector, sensor, antenna, laser, pinger, lbs, beam, multibeam, telemetry, satellite, iridium
	Omnirange	Gyroscope, ins, sensor, lbl, usbl, gps, magnetometer, fpga, satellite, iridium
	Connection type	Chain, weld, flexible, detachable
Structure dimension (Product layer)	Winch	Bracket, skid, motor, chassis, roller, cable
	Mechanical arm	Arm, chassis, joystick, telemetry, manipulator, clamp, hydraulic, motor
	Sensor	Piezoelectric, biological, chemical, flow, liquid
	Battery	Electrolyte, lithium, acid, nuclear, Ni-MH, snorkeling
	Shape	Biological, missile, fish, pinion, aerodynamic, conical, spherical, cylindrical
	Emergency localization	Tracker, strobe, rdf, hipap, transponder, gps, iridium
Material dimension (Technology + Product layer)	Buoyancy material	Foam, pvc, polyurethane, plastic, wood, polypropylene, polyethylene, nylon, fibre, pvdf
	Transmission media	Copper, fiberglass, optical fiber, semiconductor laser, led, cable,
	Body	Polymer, epoxy, fiber, carbon, composite, polypropylene, aluminum alloy, grp steel, titanium
Energy dimension (Technology + Product layer)	Energy source	Ship, battery, fuel, nuclear, generator, accumulator, hybrid electricity
	Thruster	Hydraulic, main pump, auxiliary pump, duct, brushless DC thruster
	Motion form	Concentric, collinear, column, pivot, curve, directional, bidirectional, hover
	Propeller	Electricity, hydraulic, reverse

4.4. Phase 4: MA-Based TRM for Existing Technologies and Products

In this phase, a TRM for existing technologies and products is developed based on the morphology matrix constructed in the previous phase. Each of the node consists of the core technological morphology of 2 years of patents. This is extracted based on Table 1. For example, node T1 at the bottom of the technology layer is established based on patents from 2000 to 2001, node T2 contains patents from 2002 to 2003 and the other nodes are constructed in the same manner. The left side of each node is included in the year when the target patents are applied while the right side has no practical significance. The MA

results based on the morphological matrix of each node are listed in Table 5. In Table 5, each of technology node representing 2-year technological development is depicted based on the combination of shapes.

Table 5. Technology description based on morphological analysis (MA).

Technology	Description Based on Morphology Analysis
T1	Sensor—Sonar—Omnirange system—Propeller—Capture arm—Conical body—Cylindrical Body
T2	Optical cable—Weld—Flexible connection—GPS—Capture arm—Winch—Ellipsoid body—Foam
T3	Fuel cell—Hydrocarbon—Optical cable—Acoustic detector—Turbine—Mechanical arm—Elongated hull—Tether control system—Propeller—Buoyancy system
T4	Radio communication—Cable—Acoustic localization—Propeller motor drive—Synthetic aperture sonar system—Mother ship power supply—Buoyancy components
T5	Horn shaped reconfigurable hull—Camera—Anti sonar detection—USBL—Sensor—Spherical angle—INS—Cable—Capture arm—Propulsion device—Sonar—Scintillation material—Composite—Phase change material
T6	Fuel cell—Propulsion system—Recycling cable—Clamping arm—Acoustic device—Integrated scintillation material—Artificial intelligence algorithm—Conical shell—Navigation system—Beam weapon—Sensor—Pump jet
T7	Optical cable—Winch—Localization—Sensor—Motor—Buoyancy material—Non-physical connection—Transmission medium—3D imaging sonar—INS—Mechanical connection—3-axis motion
T8	Chain connection—Braking device—Elongated hull—Mechanical arm—Sensor—Buoyancy system—Air and underwater vehicle—Carbon fiber
T9	Ultrasonic generator—Mechanical connection—Turbine engine—Camera—Battery—Pulse power hybrid electric propulsion—Buoyancy system—Ejector—Cable rope—Power source—Cylindrical shell—Capture arm—Flexible shell—Elliptical shell—Sensor—Gyro—Equipment bearing—Acoustic navigation—Winch—Wireless guidance
T10	Longitudinal axis shell wing—Propulsion system—Battery—Magnetic circuit launcher—Buoyancy material—Acoustic device—Hinge connection—Resistance fin—Wheel frame—Depth camera—Sensor—Propeller—Acoustic positioning system and GPS hybrid system—Phase change material—Pump—Energy harvester

The cosine similarity values between different patents are observed with document vectors based on Equation (1), are revealed in the Supplementary Material (Cosine distance between patent documents and cosine distance between 10 products with all patents). To build the linkages between technology nodes, the average value of each patent concerning all the other patents is calculated based on the cosine values between each document. The similarity values between the technology nodes are shown in Table 6 and are weighted in the following three steps: (a) calculate the sum of the cosine similarity values of each patent to all the other patents in 1 year and average it, (b) calculate the value of each year concerning all the other years by adding the values of patents in 1 year that are earned in step (a) and average them, and (c) calculate the values of each node compared with others by adding the values of 2 years in each node; for example, the relationship between T1 and T3 is calculated by adding the values of 2000 to 2002, 2000 to 2003, 2001 to 2002 and 2001 to 2003. In this demonstration, a similarity value greater than 0.2 is shown as a dotted line, and a similarity value greater than 0.4 is shown as a solid line.

In the product layer, configurations of different morphologies are obtained based on the selected representative underwater vehicle products. The HUGIN, LBV and etc. are the products of automated underwater vehicle (AUV) and remotely operated vehicles (ROV), which are listed as Table 7. For example, the node at the bottom of the layer indicates the morphology configuration of the HUGIN AUV under the frame of the morphology matrix. The leftmost side or rightmost side primarily indicates the time during which the product is for sale based on the product manuals and Internet information; however, to make the timeline more comprehensive, we select the time when the product is designed, such as for the HUGIN AUV and REMUS AUV. The MA result based on the morphological matrix of each product node is listed in Table 7. The product is classified into AUV and ROV and each of product node is depicted based on the combination of shapes to analyze the product development.

Table 6. The similarity between each pair of nodes in the technology layer.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
T1	1									
T2	0.150	1								
T3	0.280	0.226	1							
T4	0.356	0.254	0.211	1						
T5	0.339	0.143	0.381	0.348	1					
T6	0.528	0.199	0.234	0.383	0.436	1				
T7	0.468	0.174	0.299	0.383	0.368	0.446	1			
T8	0.512	0.131	0.281	0.338	0.345	0.425	0.457	1		
T9	0.406	0.195	0.247	0.324	0.282	0.350	0.440	0.353	1	
T10	0.371	0.096	0.198	0.196	0.245	0.355	0.313	0.268	0.33	1

Table 7. Product description based on MA.

Category	Products	Description Based on Morphology Analysis
AUV	GAVIA	Battery: lithium-ion—Communication: iridium, acoustic modem, wireless LAN—Navigation: GNSS, DGPS, DVL, LBL, USBL—Sensor: swath bathymetry module, teledyne blueview microbathymetry and gapfill, side-scan sonar, telydyne benthos sub-bottom profiler (SBP), environmental sensor—Shape: cylindrical
	SEAGLIDER	Sensor: pressure sensor, turbulence sensor—Pump: vacuum pump—Shape: wings, fish—Localization: GPS, iridium communication
	HUGIN	Sonar: side-scan sonar, synthetic aperture sonar, multibeam echo sounder, fishery sonar, laser plankton counter—Battery: lithium polymer battery, aluminum oxygen semi-fuel cell—Winch: L/R system winch—Shape: torpedo, cylindrical—Equipment carrying system: stinger ramp system
	MUNIN	Echo sounder: tailored EM 2040 multibeam—Battery: Li-ion—Sensor: paroscientific digiquartz depth sensor—Localization and communication: HiPAP acoustic positioning and communications, Iridium, wifi, cNODE acoustic command and data link—Navigation: multibeam echosounder and side-scan sonar—Shape: cylindrical
	REMUS	Navigation: LBL, GPS, INS, acoustic, WAAS, Iridium—Battery: Li-ion battery—Sonar: bathymetric side-scan sonar, gap-filler sonar—Shape: cylindrical—Localization: acoustic transponder, acoustic modem, iridium modem—Communication: acoustic modem, iridium, WiFi, Ethernet—Propulsion: DC brushless motor
ROV	LBV	Motion form: 4-axis maneuverability—Camera: high-intensity LED tracking camera, HD and zoom camera—Motor: brushless DC thruster—Equipment carrying system: reel optional, integrated tether reel with slip ring, optional wheeled crawler skid assembly with patented vortex generator—Sonar: flexible platform, imaging, scanning, profiling — Arm: three jaw—Shape: box
	REMOTEFLYER	Sonar: Didson sonar system—Movement: 4-axis translation—Motor: brushless DC motor—Propeller: stainless steel—Nozzle: nylon Kort nozzle—Camera: High-resolution color video, high-flotation jacket over Kevlar braid—Sensor: depth, heading
	MINIROVER	Sensor: heading and depth, pitch/roll—Camera: high-resolution zoom color camera and low light-level B&W—Body material: ultra-high molecular weight polyethylene—Thruster: magnetically coupled DC brushless thruster
	H-ROV	Material: stainless steel, GRP—Arm: 5-axis electric, 7-axis electric—Camera: multiple PTZ video camera—Navigation: horizontal and vertical DVL—Sonar: SSS, MBES
	SEAROVER	Camera: high-resolution color camera, ultra-low-light B&W camera, 180° tilt camera NTSC/PAL—Motion form: 3-axis translation—Propeller: Stainless steel—Nozzle: nylon Kort nozzle—Tether: dual coax—Thruster: magnetically coupled brushless thruster

To build the linkages between product nodes, the cosine similarity values between different products are determined with document vectors based on Equation (1), as presented in Table 8. In this demonstration, a similarity value greater than 0.3 is represented as a dotted line, and a similarity value greater than 0.5 is represented as a solid line. A dotted line indicates that the relationship between the two products is weak, while a solid line indicates that it is strong.

The linkage between the technology layer and the product layer is determined by calculating the cosine similarities between each product node and technology node, as shown in Table 9. In this illustration, the five largest values that are over 0.1 are selected as the guideline to link the technology layer and product layer. T2 and the product "H-ROV" are excluded from the TRM because of their low values compared with others.

After building the linkages between each technology node, product node, technology and product nodes, the MA-based TRM for existing underwater vehicle technologies and products is depicted in Figure 3. In the TRM, the technology and product trends are revealed to guide organizations to discover new opportunities and plan technology and product strategy.
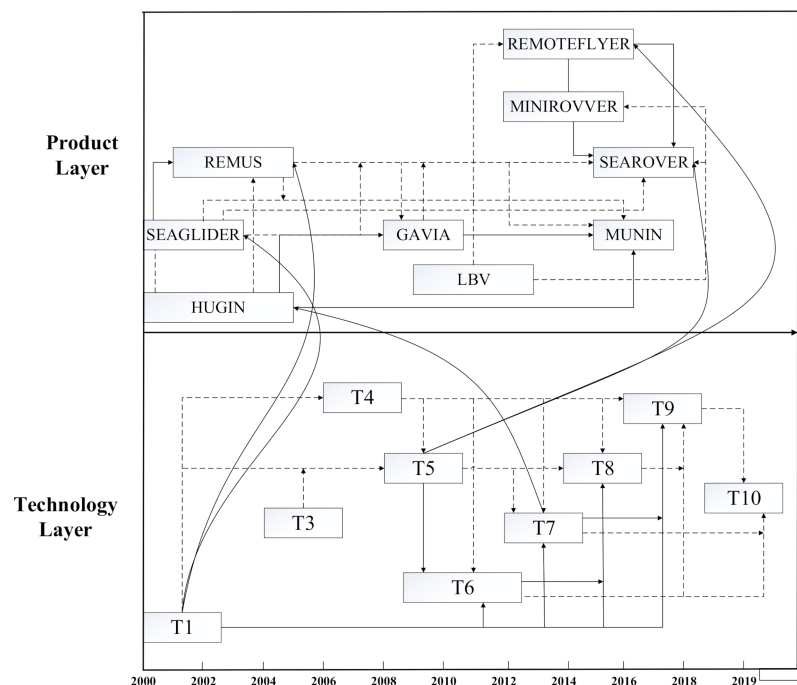

Figure 3. MA-based technology roadmap (TRM) for existing underwater vehicles.

Table 8. The cosine similarity values between products.

Products	GAVIA	H-ROV	HUGIN	LBV	MINIROVER	MUNIN	REMOTEFLYER	REMUS	SEAGLIDER	SEAROVER
GAVIA	1	0.264	0.717	0.141	0.144	0.650	0.209	0.354	0.253	0.184
H-ROV		1	0.215	0.078	0.129	0.211	0.105	0.075	0.029	0.069
HUGIN			1	0.091	0.065	0.735	0.139	0.437	0.367	0.166
LBV				1	0.431	0.095	0.359	0.205	0.103	0.332
MINIROVER					1	0.069	0.563	0.155	0.006	0.627
MUNIN						1	0.130	0.471	0.417	0.192
REMOTEFLYER							1	0.207	0.185	0.634
REMUS								1	0.670	0.410
SEAGLIDER									1	0.346
SEAROVER										1

	GAV	HUG	LBV	MINI	MUN	REMO	REMU	SEAG	SEAR
T1	0.0674	0.0879	0.0389	0.0229	0.1102	0.054	0.1693	0.1502	0.085
T3	0.0755	0.1151	0.0201	0.0258	0.0909	0.0376	0.089	0.0882	0.0366
T4	0.0891	0.0744	0.0376	0.0502	0.0632	0.1301	0.0661	0.0786	0.0721
T5	0.1023	0.0966	0.0862	0.0776	0.0844	0.1521	0.1033	0.0907	0.1281
T6	0.0838	0.1009	0.0385	0.0185	0.0926	0.1025	0.1445	0.1458	0.1146
T7	0.1278	0.1444	0.0382	0.047	0.1119	0.0624	0.1375	0.1418	0.067
T8	0.0952	0.1064	0.0323	0.0482	0.0918	0.0724	0.1147	0.1156	0.0557
T9	0.0782	0.092	0.0385	0.1041	0.0782	0.1013	0.0894	0.1118	0.0573
T10	0.0574	0.0826	0.0369	0.0495	0.0765	0.0772	0.0587	0.0749	0.0838

4.5. Phase 5: MA-Based TRM for New Technologies and Products

In the process of identifying new technologies and products, the SGTM-based maps are developed and TRIZ inventive principles are applied in systematizing the innovation path with the experts' aid. In the SGTM-based map, a series of cells that contain the keywords are scattered to divide the whole map into different parts, thus generating dense areas and sparse areas. The sparse areas are the targets for identifying new technologies and products, as there have been rare attempts to address technology opportunities in these areas. The sparse areas that contain fewer than two words are identified. The SGTM-based maps of the technology layer and product layer are shown as Figures 4 and 5. For example, in Figure 4 (technology), the areas "titanium" and "composite", which are isolated from the others, are considered to be technology vacuums. Similarly, the areas "pump", "generator", "chain", "battery", "lithium", "telemetry", "detector", "sonar", "camera", "propeller" and "duct" are defined as technology innovation sources. In Figure 5, the areas "steel", "titanium", "battery", "lithium", "telemetry", "sonar", "camera" and "hydraulic" are identified as product innovation sources.
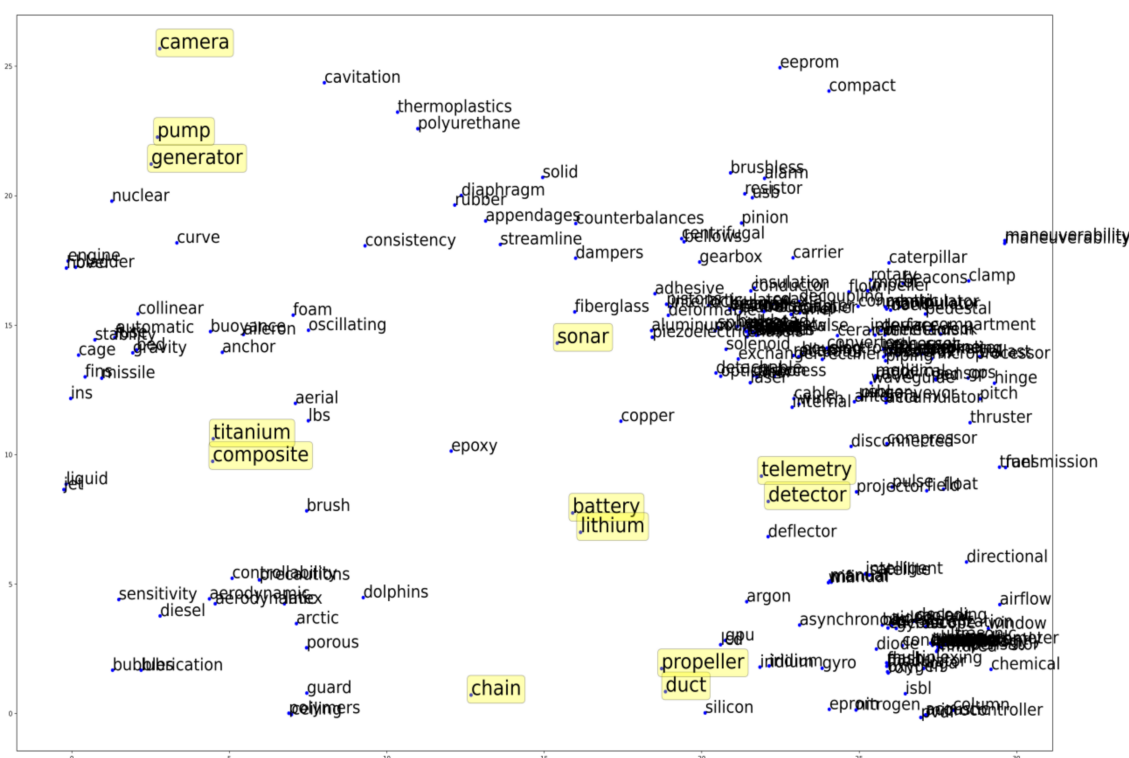

Figure 4. Sparse generative topographic mapping (SGTM)-based map for technologies.

Figure 5. SGTM-based map for products.

For the step of utilizing the TRIZ inventive principles, to extract the most suitable inventive principles efficiently, each of them is first generalized in the form of keywords based on the definition. Then, the appearance frequency of the keywords in the patent documents are counted and recorded in Python. Consequently, the 40 TRIZ inventive principles are ranked to identify new technologies and products systematically, as shown in Table 10. The description of the 40 motivated principles is given in the Appendix C. The essential result of the occurrence frequency of extracted TRIZ keywords is listed in Appendix D. Keywords whose occurrence frequency is up to 199 are selected to identify suitable innovative principles. In particular, considering the target field complex features and the characteristics of the developing era, we introduced a new inventive principle called "intelligentization" in order to make the innovation process more efficient and significant. The principle of "intelligentization" is defined based on modern communication, information technology, computer network technology, industry technology and intelligent control technology, implemented an automated and intelligent management and control process from perception to memory and then the automation of thinking and execution in a certain production process.

Table 10. The relevant theory of inventive problem solving (TRIZ) innovative principles in the field of underwater vehicles.

Keyword	Count	Corresponding Principles
recover	2445	34 Discarding and recovering
move	2043	17 Another dimension
thin	1444	30 Flexible shells and thin films
add	1398	22 "Blessing in disguise" or "Turn lemons into lemonade"; 39 Inert atmosphere
acoustic	1386	28 Mechanical substitution

The innovation path in applying the TRIZ inventive principles in sparse areas is demonstrated as follows: First, the areas "titanium" and "composite" in Figure 4 and "steel" and "titanium" in Figure 5 are influenced by the principle of "Mechanics substitution". This means that the material of

the composite can be improved and substituted to some extent by titanium, which may be a research target in the next few years and is represented by N1. It is relevant to new technologies and products. Second, several principles may generate synergistic effects together in this area. The principles of "Spheroidality-Curvature", "Dynamics" and "Flexible shells and thin films" share a similar meaning of "making the shape, function, phase, or action smooth and the moving rate low, etc.". The principles of "self-service" and "intelligentization" are used with the above three inventive principles, which help experts find potential technologies related to intelligent driving materials, driving motion without mechanical joints and bionic propulsion motion in the sparse areas of "pump" and "generator" in Figure 4. In addition, the product's structure could be developed into detachable and highly deformable structures between the overall and local structures. The new opportunities are represented by N2. Third, the sparse areas "battery" and "lithium" in Figure 4 and "battery" and "lithium" in Figure 5 can lead experts to identify new technologies and products. The mainstream battery is in the category of solid lithium-ion batteries in the field of underwater vehicles. Therefore, the principle of "parameter changes" is applied in identifying potential valuable developing targets of semi-solid batteries, which is represented by N3. Fourth, the sparse areas "telemetry" and "detector" in Figure 4 and "telemetry" in Figure 5 are considered part of the technology of route planning. With the influence of the principle of "intelligentization", N4 represents that route planning based on artificial intelligence algorithms and machine learning is waiting to be designed. Fifth, the sparse area "camera" in Figures 4 and 5 could be influenced by the principle of "another dimension". N5 represents that new technologies and products could be defined as designing a camera that utilizes 360-degree surround-view VR technology. Finally, the research field of propulsion methods is identified by the areas of "propeller" and "duct" in Figure 4 and "hydraulic" in Figure 5. The normal propulsion methods include propellers, hydraulics, water jets, magnetic fluids, bionics and crawlers. The principle of "merging" is conducted to refine the area with the results of blending one propulsion method with another, such as by combining propeller and bionic propulsion which is represented by N6. The effective inventive principles in the innovation path of excavating potential technologies and products are shown in Figure 6. The description of new opportunities is discussed in the next section. The new technologies and products listed in this study do not represent all technological opportunities. These results are listed to show the plausibility and scientific nature of the proposed approach. The MA-based TRM of underwater vehicles for new opportunities is presented in Figure 6. The application process of TRIZ is depicted in Figure 6 by showing the number or name of the principles on each linkage.
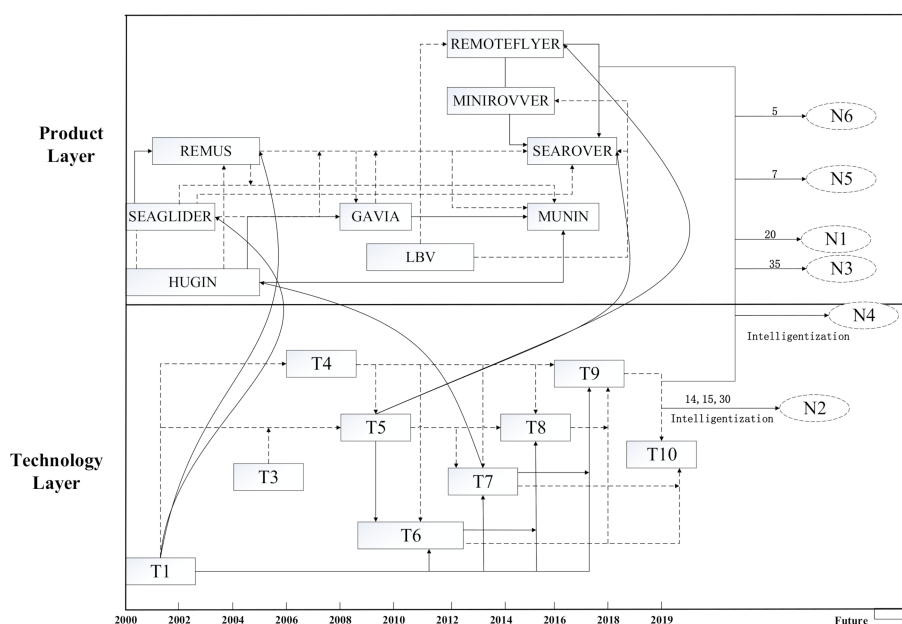

Figure 6. The MA-based TRM of underwater vehicles for new opportunities.

5. Discussion

In sum, the roadmapping framework that we have built could be analyzed from three essential parts that cover the features of the proposed approach. The first part lies in the nodes which are set to depict the implication of extracted technology or product. Research by Jin et al. [2] defined nodes by the aid of patent document while research by Lee and Geum [78] utilized the concept of scenarios in order to build nodes. In comparison, we built nodes in Tables 5 and 7 with the aid of keyword-based MA which could decompose target fields hierarchically and systematically similar to Yoon et al. [4]. Secondly, the linkage between layers is essential to analyze. The pair of nodes with a high similarity value indicates a high probability to conduct coordinated development, which was depicted in Tables 6, 8 and 9. Researches by Hansen et al. [79] and Yoon et al. [4] established the linkage between technology and product layer based on the technology-product link matrix, evidencing that the relationship between technology and product layer could be measured by the similarity. Thirdly, the process of identifying new opportunities from existing TRM is established in a novel way. The process refers to two aspects. One relates to the analysis of the technology and product development trends in a dynamic perspective based on SGTM map. Kaneko [73] modified the conventional GTM algorithm and achieved simultaneous data visualization and clustering in a dynamic perspective, which is utilized in this study to identify sparse and dense innovation areas. The other one refers to the application of TRIZ inventive principles. Research by Moehrle [80] confirmed the validity of integration between TRIZ and TRM, in which the evolutionary patterns of technical systems are utilized to elaborate the structure and composition of TRM. In this study, TRIZ inventive principles are particularly introduced in order to impact on the innovation elements derived from innovation sparse areas.

As can be seen in Table 11, six new technology and product opportunities in the technology–product MA-based TRM are derived from the sparse areas in a hybrid way which contains quantitative and qualitative tools. New technologies hasten new products, while the related conception of new products will promote the development of new technologies accordingly. For example, as an alternative material, the usage of titanium metal could improve the mechanical performance of underwater vehicles to a certain extent. As for the practical production, it will depend on the level of technology development, which is related to production cost. The derived new opportunities represent a development trend to direct the organizations to plan technology and product strategy. Therefore, how to utilize the discovered new opportunities in practical production is another important decision making aspect. It should be noted that the application of each opportunity is not mandatory, since whether a firm prevent all kinds of unexpected things or not is simply a matter of decision, if a firm does not possess enough resources and capabilities.

Traditional MA-based TRM provides a standard form to utilize morphology configuration to identify technology opportunities. Yoon et al. [4] established the morphological matrix of mobile phone technologies and products mainly based on expert's participation and identified technology opportunities by substituting the components of technology and product configurations. Compared with that, the results of this article reveal the technology and product development trends with a further quantitative analysis in the identification of sparse and dense innovation areas, which make the process of identifying new opportunities systematic. According to the technology and product trends, we define new opportunities by the aid of TRIZ inventive principles.

Several policies of the proposed approach are worth noting. First, the improved inventive principle called "intelligentization" was proposed on account of the particularity and complexity of underwater vehicle field. It contained the potential to be applied to other complex research field. Second, in this case, organizations were not discussed. The research target aimed at the extracted technologies and selected representative products. The relationship between products, technologies and organizations was not discussed. Additionally, the MA-based TRM was constructed based on the patent documents and product manuals and could be applied by different organizations. Thus, specific organizations were not discussed in this case. Third, the process of MA and applying TRIZ inventive principles into the variation of innovation sources in sparse areas were performed at the implemented level. Although

there are previous literatures focusing on the integration between MA and TRM [4,9], the proposed approach differs from them in the application of TRIZ inventive principles in the process of discovering promising opportunities from existing MA-based TRM.

Table 11. New opportunities discovered by integrating TRIZ inventive principles.

New Opportunities	Innovation Sources in Sparse Area	TRIZ Inventive Principles (Improved)	Description of New Opportunities
N1	Titanium, composite (technology), Steel, titanium (product)	28. Mechanics substitution	The total amount of titanium metal is large. And its strength is strong with the strong ability to resist acid and alkali corrosion. It will not be corroded when immersed in seawater before 5 years. The underwater vehicle made of titanium alloy can dive to a depth of several kilometers. Moreover, the cost is not high.
N2	Pump, generator (technology)	14. Spheroidality-Curvature, 15. dynamics, 25. self-service, 30. flexible shells and thin films, intelligentization (improved)	First, the use of intelligent driving materials can effectively improve the propulsion speed and propulsion efficiency of the underwater vehicles, not only making the structure of the vehicles more simplified and compact, but also improving the concealment of the vehicle's underwater movement, which can realize silent movement. Second, the driving mode with no machinery joints can better realize the continuous and flexible movement of the vehicle.
N3	Battery, lithium (technology) Battery, lithium (product)	35. Parameter changes	The positive electrode of the lithium battery using a full gradient composite material can improve the cycle performance. The negative electrode using nanometer materials has the advantage of excellent reversible cycle capacity. The battery form should develop from solid to semisolid, which can improve safety performance.
N4	Telemetry, detector (technology) Telemetry (product)	Intelligentization (improved)	Technology based on artificial intelligence algorithms and machine learning to plan paths can effectively optimize the safety and flexibility of underwater vehicles.
N5	Camera (technology) Camera (product)	17. Another dimension	The 360-degree surround view virtual reality (VR) technology of the camera allows researchers to have a better view when exploring the seabed.
N6	Propeller, duct (technology) Hydraulic (product)	5. Merging	The use of two or more hybrid propulsion methods including propellers, hydraulics, water jets, magnetic fluids, bionics, and crawlers can make the motion of underwater vehicle more flexible and stable.

6. Conclusions

In this paper, to construct a layer expansion path, we proposed a method to develop the concept of MA-based TRMs by applying the 40 TRIZ principles with an improved principle and text mining tools, which are considered as effective tools for technology and product planning and for seeking potential valuable opportunities, by analyzing the morphology of patents and product manuals in the targeted field. We assumed that it was reasonable for a firm to have new technology that has not been used in products and markets yet as well as systematized documents describing the technology and that such firms seek new business opportunities through roadmapping. The MA-based TRM possessed not only the capability of decomposing the complex research field hierarchically but also the joint of linking with TRIZ inventive principles. The process of establishing MA-based TRM acquired text mining tools as auxiliary to link each pair of nodes quantitatively to decrease the intervene of experts,

which didn't mean the experts pale into insignificance. The execution of MA required the detailed understanding of the outline of the research field while TRIZ required the priority of applied inventive principles. The potential valuable opportunities were extracted based on the influence between TRIZ inventive principles and sparse innovation areas in the TRM. Since our approach depended on the exploratory method, an idea based on the morphological analysis of technological documents and product manuals was developed and tested to seek potential valuable technologies and products effectively in sparse areas. The MA-based TRM, which was constructed by structural and visualized morphology configurations, was determined by analyzing technological document information and quantitatively excavating technological features, and thus could be applied into different fields.

This study makes contributions to the field in three ways. First, in terms of data, patent documents were collected from the USPTO database, which has been utilized or advised to be utilized to analyze technological features [63], and the product manuals were collected from professional websites. The data information was processed by text mining tools without much expert participation. Second, regarding the proposed methodology, as traditional processes for drawing a TRM use techniques experts preferred, the systematic proposed process that considers layer expansion paths in exploring new business opportunities was conducted based on the concepts of MA and TRIZ, which analysts regularly derive standard outputs from. The simplified process was suggested to improve the TRIZ complex system. Finally, the application to the field of underwater vehicles was explorative and heuristic in seeking potential valuable technologies and products for new business opportunities in the underwater vehicle field. As a result, this paper extends the application areas of MA and TRIZ by applying them to the technology roadmapping process.

Although contributions have been made to this field, there are some limitations in this paper. First, this paper explores complex methodologies appropriate for each layer to break down each barrier to scientific research. Although the use of text mining tools could address the massive amount of text processing work and analyze the interrelationships of the target field by turning unstructured data into structured data, it is sometimes too difficult to integrate massive approaches with the same aim due to multiple possibilities in sequences constrains related to the linkage in technology and product layers and other layers are not explored, which would be more complicated on account of more influence factors. Second, the process of seeking new technologies and products focuses on constructing a systematic path without considering the temporal attributes of the newly excavated technologies and products, meaning that the appearance time is not predicted in this study, which may weaken the timeliness of strategic planning formulated by enterprises and thereby affect the economic benefits of enterprises. Third, this methodology generally concentrates on quantitative analysis, but experts' help is in need in the process to screen central keywords among the results of text mining. The expert intervention problem for this screening process will decrease the efficiency of application of the text mining approach. Finally, this study presents only an explanatory case study rather than a real one. Although the product layer is established based on the products on the market, an application to a real case will be in need to analyze the feasibility of the method and confirm its validity. The potential value of derived opportunities in the whole industry are not calculated so that the priority of each opportunity could not be presented, which need further assessment by strategy planners.

In addition to overcoming the above mentioned limitations, further studies should be carried out on the concept of integrating TRMs with other roadmapping processes. This research will be a step towards a wider and more inspirational understanding of TRMs. Therefore, future studies should promote the development of MA-based TRMs and other new concept roadmaps to provide a platform for the integration of multiple methodologies. Besides, the application of TRIZ in the MA-based TRM is heuristic and is considered pioneering in its aim to simplify the application process of the TRIZ system. As the TRIZ system contains multiple effective tools and a complete application process for conducting technology innovation, future research could focus on the associated application of other tools with innovative principles in other research fields, such as technology opportunity discovery, product design and enterprise strategic planning. Furthermore, this paper selects the technology layer

and product layer as the targets to demonstrate the proposed approach. Hence, future research could select the other two layers, the market layer and service layer, as additional research targets to propose a systematic procedure for constructing a complete TRM. In regard to the establishment and evaluation in product and service layer, customer-oriented Kansei evaluation [81] as a potential direction could be taken for a bidirectional bridge to link the two layers which equally contains the potential to be applied into the two layers with other layers. Finally, from the perspective of determining the appearance time, various factors, such as a short technology life cycle and relevant mathematical models, could be proposed and improved in order to predict the timing of the replacement of incumbent technology and products with new products, such as by using the Bass diffusion model [64] and logistic model [82] in future research.

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Appendix A

Table A1. K-means clustering results of technology keywords.

Cluster_ID	0	1	2	3	4	5	6	7	8
Word	flash automatic transmission processor solid window float fuel bulkhead polyurethane roller clamp directional impeller hover	acoustic gps usbl iridium ins	generator maneuve-rability chain fuse	cable	panel gyro	field intelligent concurrently	winch chassis usb foam conductor titanium pump fins	connector	bearing carbon arctic dock

Cluster_ID	11	12	13	15	17	18	19	20	21
Word	optical lbl antenna backscatter wifi	sonar	internal fiber lcd composite jet converter	oxygen	battery lbs motor pitch propeller	profiler multibeam detector projector	interface satellite modem aided beacons	recorder pinger radio stability compartment chemical	manipulator telemetry device mechanism

Cluster_ID	24	28	29	26	9	10
Word	laser beam magnetometer bracket flow	deck ethernet manual	access nuclear biological	brushless thruster	camera led light sensitivity	lithium housing umbilical pulse aluminum ballast copper

Appendix B

Table A2. K-means clustering results of product keywords.

Cluster_ID	0	1	3	4	6	7	8
Word	iridium adcp acoustics locator xenon impeller	sensor gps strobe telemetry laser altimeter transponder transmission antenna metal didson echosounder hipap polyurethane	sonar	skid crawler plastic beam winch minirov chassis wood polypropylene container nuclear ahrs polymer foam acrylic transmitter pvc conductor glass	ethernet transducer generator hydrophone body hydraulic buoy magnetometer receiver bandwidth micro usb wifi rdf bulkhead filter adds tracker	material	manipulator 8 console 8 joystick 8 motor 8 arm 8 lcd 8 waterproof 8 gyro 8 halogen 8 nylon 8 grp 8 lamp 8

Cluster_ID	10	11	12	13			
Word	cable battery lithium connector	steel energy fiber aluminium polyethylene copper titanium	speed bollard	camera video ccd			

Appendix C

Table A3. List of TRIZ inventive principles.

Principle	Title	Description	Keywords
1	Segmentation	1. Divide an object into independent parts. 2. Make an object easy to disassemble. 3. Increase the degree of fragmentation or segmentation.	divide, replace
2	Taking out	1. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.	separate
3	Local quality	1. Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform. 2. Make each part of an object function in conditions most suitable for its operation. 3. Make each part of an object fulfill a different and useful function.	change, nonuniform
4	Asymmetry	1. Change the shape of an object from symmetrical to asymmetrical. 2. If an object is asymmetrical, increase its degree of asymmetry.	change, asymmetrical
5	Merging	1. Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations. 2. Make operations contiguous or parallel; bring them together in time.	Assemble, merge
6	Universality	1. Make a part or object perform multiple functions; eliminate the need for other parts.	multiple, eliminate
7	Nested doll	1. Place one object inside another; place each object, in turn, inside the other. 2. Make one part pass through a cavity in the other.	inside, nest
8	Anti-weight	1. To compensate for the weight of an object, merge it with other objects that provide lift. 2. To compensate for the weight of an object, make it interact with the environment (e.g., use aerodynamic, hydrodynamic, buoyancy and other forces).	compensate, weight
9	Preliminary anti-action	1. If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with antiactions to control harmful effects. 2. Create beforehand stresses in an object that will oppose known undesirable working stresses later on.	anti-action, beforehand, replace

Table A3. *Cont.*

Principle	Title	Description	Keywords
10	Preliminary action	1. Perform, before it is needed, the required change of an object (either fully or partially). 2. Prearrange objects such that they can come into action from the most convenient place and without losing time for their delivery.	prearrange, preliminary
11	Beforehand cushioning	1. Prepare emergency means beforehand to compensate for the relatively low reliability of an object.	beforehand, prepare
12	Equipotentiality	1. In a potential field, limit position changes (e.g., change operating conditions to eliminate the need to raise or lower objects in a gravity field).	change
13	The other way around	1. Invert the action(s) used to solve the problem (e.g., instead of cooling an object, heat it). 2. Make movable parts (or the external environment) fixed, and fixed parts movable). 3. Turn the object (or process) ternal environ	invert, turn, movable
14	Spheroidality-Curvature	1. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures. 2. Use rollers, balls, spirals, domes. 3. Go from linear to rotary motion, use centrifugal forces.	spherical, roller, ball, spiral, dome, rotary
15	Dynamics	1. Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition. 2. Divide an object into parts capable of movement relative to each other. 3. If an object (or process) is rigid or inflexible, make it movable or adaptive.	change, movable, flexible
16	Partial or excessive actions	1. If 100% of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.	partial, excessive
17	Another dimension	1. To move an object in two- or three-dimensional space. 2. Use a multistory arrangement of objects instead of a single-story arrangement. 3. Tilt or reorient the object, lay it on its side. 4. Use 'another side' of a given area.	tilt, move, dimensional, multistory

Table A3. *Cont*.

Principle	Title	Description	Keywords
18	Mechanical vibration	1. Cause an object to oscillate or vibrate. 2. Increase its frequency (even up to the ultrasonic). 3. Use an object frequency (even up to the ultrasonic) tric vibrators instead of mechanical ones. 4. Use piezoelectric vibrators instead of mechanical ones. 5. Use combined ultrasonic and electromagnetic field oscillations.	oscillate, vibrate, frequency
19	Periodic action	1. Instead of continuous action, use periodic or pulsating actions. 2. If an action is already periodic, change the periodic magnitude or frequency. 3. Use pauses between impulses to perform a different action.	periodic, impulse
20	Continuity of useful action	1. Carry on work continuously; make all parts of an object work at full load, all the time. 2. Eliminate all idle or intermittent actions or work.	continuous, eliminate
21	Skipping	1. Conduct a process, or certain stages (e.g., destructible, harmful or hazardous operations) at high speed	skip, fast
22	"Blessing in disguise"or"Turn Lemons into Lemonade"	1. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect. 2. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.	turn, add
23	Feedback	1. Introduce feedback (referring back, cross-checking) to improve a process or action. 2. If feedback is already used, change its magnitude or influence.	feedback, introduce, change
24	Intermediary	1. Use an intermediary carrier article or intermediary process. 2. Merge one object temporarily with another (which can be easily removed).	intermediary, merge
25	Self-service	1. Make an object serve itself by performing auxiliary helpful functions 2. Use waste resources, energy, or substances.	self-service, serve, recycle
26	Copying	1. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies. 2. Replace an object, or process with optical copies. 3. If visible optical copies are already used, move to infrared or ultraviolet copies	copy

Table A3. *Cont.*

Principle	Title		Description	Keywords
27	Cheap short-living objects	1.	Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).	cheap, inexpensive
28	Mechanics substitution	1.	Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.	replace, interact, optical, acoustic, taste, smell, electric, magnetic, electromagnetic
		2.	Use electric, magnetic and electromagnetic fields to interact with the object.	
		3.	Change from static to movable fields, from unstructured fields to those having structure.	
		4.	Use fields in conjunction with field-activated (e.g., ferromagnetic) particles.	
29	Pneumatics and hydraulics	1.	Use gas and liquid parts of an object instead of solid parts (e.g., inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).	gas, inflatable, liquid, replace
30	Flexible shells and thin films	1.	Use flexible shells and thin films instead of three-dimensional structures	flexible, thin
		2.	Isolate the object from the external environment using flexible shells and thin films.	
31	Porous materials	1.	Make an object porous or add porous elements (inserts, coatings, etc.).	porous, pore, introduce
		2.	If an object is already porous, use the pores to introduce a useful substance or function.	
32	Color changes	1.	Change the color of an object or its external environment.	change, color, transparency
		2.	Change the transparency of an object or its external environment.	
33	Homogeneity	1.	Make objects interacting with a given object of the same material (or material with identical properties).	interact, same, identical
34	Discarding and recovering	1.	Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.	discard, recover
		2.	Conversely, restore consumable parts of an object directly in operation.	
35	Parameter changes	1.	A Change an objects consumable state (e.g., to a gas, liquid, or solid.	change, gas, liquid, solid, temperature, flexibility, concentration, consistency
		2.	Change the concentration or consistency.	
		3.	Change the degree of flexibility.	
		4.	Change the temperature	

Table A3. *Cont*.

Principle	Title	Description	Keywords
36	Phase transitions	1. Use phenomena occurring during phase transitions (e.g., volume changes, loss or absorption of heat, etc.)	change, volume, heat
37	Thermal expansion	1. Use thermal expansion (or contraction) of materials. 2. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.	expand, thermal
38	Strong oxidants	1. Replace common air with oxygen-enriched air. 2. Replace enriched air with pure oxygen. 3. Expose air or oxygen to ionizing radiation. 4. Use ionized oxygen. 5. Replace ozonized (or ionized) oxygen with ozone.	replace, oxygen
39	Inert atmosphere	1. Replace a normal environment with an inert one. 2. Add neutral parts, or inert additives to an object.	replace, add, neutral, inert
40	Composite materials	1. Change from uniform to composite (multiple) materials.	change, composite, material

Appendix D

Table A4. Result of the occurrence frequency of extracted TRIZ keywords.

TRIZ Keywords	Frequency	Corresponding Principles	TRIZ Keywords	Frequency	Corresponding Principles
recover	2445	34 Discarding and recovering	ball	419	14 Spheroidality-Curvature
move	2043	17 Another dimension	turn	411	13 The other way round; 22 "Blessing in disguise" or "Turn Lemons into Lemonade";
thin	1444	30 Flexible shells and thin films	merge	409	5 Merging; 24 Intermediary
add	1398	22 "Blessing in disguise" or "Turn Lemons into Lemonade"; 39 Inert atmosphere	inside	358	7 Nested doll;
acoustic	1386	28 Mechanics substitution	separate	338	2 Taking out
electric	1166	28 Mechanics substitution;	thermal	337	37 Thermal expansion
roller	1076	14 Spheroidality-Curvature	optical	320	28 Mechanics substitution
gas	937	29 Pneumatics and hydraulics; 35 Paramet-er changes	multiple	313	6 Universality
change	930	23 Feedback; 32 Color changes; 35 Parameter changes; 36 Phase transitions; 40 Composite materials	partial	309	16 Partial or excessive actions
magnetic	889	28 Mechanics substitution	Temperature	308	35 Parameter changes
movable	537	13 The other way round; 15 Dynamics	fast	236	21 Skipping
material	492	40 Composite materials	heat	217	36 Phase transitions
weight	460	8 Anti-weight	flexible	208	15 Dynamics; 30 Flexible shells and thin films
volume	448	36 Phase transitions	serve	199	25 Self-service

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